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COLD STARTUP AND LOW TEMPERATURE PERFORMANCE OF THE BRAYTON-CYCLE ELECTRICAL SUBSYSTEM

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ABSTRACT

Cold performance tests and startup tests were conducted on the Brayton-cycle inverter, motor-driven pump, dc supply, speed control with parasitic load resistor and the Brayton control system. These tests were performed with the components in a vacuum and mounted on coldplates. A temperature range of +25 to -50°C was used for the tests. No failures occurred and component performance gave no indication that there would be any problem with the safe operation of the Brayton power generating system.

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SUMMARY

Cold performance tests and startup tests were conducted on the Brayton-cycle inverter, pump-motor assembly, dc supply, speed control with the parasitic load resistor and the Brayton control system. These tests were performed with the components in a vacuum mounted on Brayton cycle coldplates. A temperature range of +25 to -50°C was used for the tests. The most significant results were:

1. The Brayton cycle subsystem operated successfully over the temperature range tested and gave no indication of any possible problem.

2. The efficiency of the inverter-pump-motor assembly combination decreased from 16 percent to 13 percent as temperature decreased.

3. The output voltage of the inverter and the dc supply were independent of temperature. Also, the speed control performance was independent of temperature.

4. The battery charger trip points were essentially independent of temperature.

5. The Brayton control system speed alarm set points showed a small (2 percent) increase in speed as temperature decreased.

INTRODUCTION

An isotope Brayton-cycle space power system is being investigated at the NASA Lewis Research Center. This system has a useful electric power output of 2 to 15 kilowatts and is completely self-contained in that it requires no external inputs other than heat. The output of the system is regulated 120/208-volt, three-phase, 1200-hertz power. For more information on the Brayton-cycle power system see references 1 and 2.

The electrical subsystem (ref. 3) of the Brayton power system regulates and distributes the generated electrical power; in addition, it provides all logic and control functions required to operate the power system.

The primary tasks of the electrical subsystem are:

1. Control alternator voltage and frequency.

2. Provide internal source of dc power.

3. Provide signal conditioning for instrumentation functions.

4. Provide system control and protection.

In a space environment, the Brayton system will be subjected to low-temperature extremes during startups. Most, but not all, Brayton electrical subsystem components have been individually tested at low temperatures by the contractors (see refs. 4-6). The purpose of this test is to determine the operation and performance of the complete electrical subsystem under cold startup conditions. The performance of components and system interactions were investigated over a temperature range of 25°C to -50°C. This was achieved by cold-soaking the nonoperating electrical subsystem to the specified temperatures prior to each simulated startup.

TEST DESCRIPTION

The Brayton cycle electrical subsystem consists of the Electrical Control Package (ECP), the Parasitic Load Resistor (PLR), the DC power supply, the signal conditioner, the control and monitor panel, two inverters, two motor-driven pumps, and two batteries. These are shown schematically in figure 1. The batteries were not available for testing, and the control and monitor panel was not built for a vacuum environment or low-temperature operation. The electrical components, except for the batteries and the control and monitor panel were mounted on cold plates and tested in a vacuum chamber over a temperature range of 25 to -50°C. The actual data were taken at a coldplate temperature of 25, -20, -30, -40, and -50°C.

The ac power supply for the subsystem was a variable-frequency, variable-voltage motor-generator (M-G) set. This M-G set was the electrical equivalent of the Brayton-cycle alternator but not the mechanical equivalent. The speed and voltage regulation of the M-G set was independent of the Brayton speed and voltage regulator contained within the ECP.

A battery simulator was used instead of the electrical subsystem batteries since batteries were not available for testing.

The electrical components were mounted on Brayton-cycle coldplates. These coldplates are cooled by pumping oil through them with the PMA's. Heat is rejected to a heat exchanger filled with gaseous nitrogen that cooled the oil. During the cold-soak, a Brayton coolant pump (the secondary coolant pump) was used to pump the oil through the system, the secondary pump having an

external supply of power. The Brayton-cycle inverter was not used and, therefore, did not introduce heat into the system. The vacuum chamber walls were also cooled with gaseous nitrogen to the same temperature as the coldplates.

The flow of gaseous nitrogen through the heat exchanger determined the temperatures of the test. The time required to cool the system down to a new temperature was between 3 and 6 hours. The system was started after all temperatures in the vacuum tank were within $\pm 2^{\circ}C$ of the desired test point. At that time, the secondary pump was turned off, and the Brayton-cycle electrical subsystem was started using the battery simulator for power and the Brayton system primary pump for cooling. The primary pump, primary inverter, signal conditioner, and control and monitoring panel were on. A data scan was taken using a computerized data acquisition system. The data taken included all voltages and currents in the Brayton electrical subsystem and 96 temperatures monitoring the subsystem and vacuum tank. After the data were taken, converted to engineering units and printed out, ac power was applied to the electrical subsystem from the M-G set. The dc supply took over the load of the battery simulator, and the electrical control package (ECP) was turned on. This sequence is typical of a space startup.

The vehicle load was set at 4.5 kW, and the frequency was set so that the parasitic-load power was 6 kW. An automatic data scan was taken at this point, after which the battery-charger data, the Brayton Control System data, and speed control data were collected. By this time, most temperatures had reached their steady-state value. The system was then shut down and a new steady-state temperature was selected.

RESULTS AND DISCUSSION

Cooling System

Motor-Driven Pump.- The motor-driven pump was tested with the inverter as a source of power. The results of the data taken on the PMA are shown in figures 2, 3, and 4.

The pump input power, inverter output power (figure 2), increased approximately 50 percent as the coldplate temperature decreased from +25 to $-50^{\circ}C$.

The flow through the pump (figure 3) decreased significantly as the temperature decreased due to an increase in viscosity. The speed of the pump remained constant at 11350 $\pm$1.0 percent. (The maximum error in the speed measurement is 1 percent.)

The pump efficiency as a function of temperature is shown in figure 4. Although the data were obtained with two different power sources, the difference between the two curves is due to the time

difference between data scans. The data for the PMA using the dc supply to power the inverter was taken approximately 20 minutes after the data using the battery simulator were taken. Thus, the temperature of the PMA and cooling oil had increased. If the data were plotted as a function of oil temperature, the dc supply curve would shift to the right, but the battery simulator curve would remain unchanged.

The temperatures monitored in the pump were the base plate, the case, and the stator end turn. Over a period of one hour after startup, the case and base plate temperatures did not change with respect to the cold plate temperature; the stator end turn temperature increased about 3°C above the cold plate temperature.

Inverter. - The inverter was tested using the pump as a load and was powered by either the battery simulator or the dc power supply. Figure 2 indicates that as the temperature decreased, the load requirements increased due to the increase in power required by the pump to pump oil through the coolant loop. From reference 7, it has been determined that as the load of the inverter increases, the efficiency increases. Thus, an increase in efficiency would result as the temperature decreased. The performance data of the inverter measured in this test indicated an even greater increase in efficiency as the temperature decreased than estimated from reference 7.

Figures 5 and 6 show the inverter efficiency curves. The upper curves are the actual efficiencies observed as a function of coldplate temperature. The lower curves are the efficiency curves that would be expected as a result of the increase in load only. The lower curves were generated by using the efficiency versus power curves at room temperature (approximately 25°C) (see ref. 7).

In figure 5, the inverter was being powered by the battery simulator and the data were taken within five minutes of startup. In figure 6, the inverter was being powered by the dc supply. The data were taken approximately 20 minutes after startup and the load had decreased significantly since startup. This was probably due to an increase in temperature of the cooling oil resulting in a decrease in load, and accounted for the decrease in observed efficiency for a given coldplate temperature.

The battery simulator voltage varied from ±27.6 to ±30.4 volts. The average inverter line-to-neutral output voltage varied from 26.3 to 29.1 volts rms. The ratio of the line-to-neutral inverter output voltage to the input voltage remained a constant of 0.958 ±0.006 over the temperature range used for these tests.

The temperatures monitored in the inverter were the output transistor case temperature, the input inductor winding temperature, and the base plate temperature. Steady-state temperatures were reached after about 1½ hours of operation. The typical temperature rise above the coldplate temperature was 34°C for the

output transistor, 21°C for the inductor, and 10°C for the baseplate.

Pump-Inverter Combination.- Because the pump and the inverter were designed to be operated together, the efficiency of the combination is of some interest. As the temperature decreased from 25°C to -50°C, the efficiency of the pump (electric to hydraulic) went down from 20.5 percent to 14 percent (fig. 4). Also, the inverter efficiency went up from 79 percent to 93 percent (fig. 5). The product of the efficiencies is the efficiency of the PMA-inverter combination. As the temperature decreased from 25°C to -50°C, the efficiency of the combination decreased from 16 percent to 13 percent.

DC Power Supply

The dc power supply (ref. 8) input power varied from 900 watts to 1 kilowatt over the temperature range of 25 to -50°C. The load varied from 780 to 870 watts and the efficiency remained constant at 87 percent. The efficiency was not affected by temperature over the range tested.

The average ac input was held constant during the test at 115±1 volts rms. The output voltage of the dc supply remained constant at 28.8 ±0.3 volts dc on both the positive and negative busses. The ratio of output dc voltage to input ac voltage (0.250 ±0.002) was not affected by temperature.

The temperatures monitored in the dc supply were the baseplate and both power transformers (thermocouples were glued on the windings). The baseplate temperature increased about 10°C above the coldplate temperature. One power transformer increased 34°C and the other transformer increased 51°C above the coldplate temperature.

The battery chargers (one for each battery) built into the dc supply have four trip points which determine the charge rate as a function of battery voltage. One operates at 30.5 volts to turn the charger on to a 4 ampere charge rate, one at 30.0 volts to increase the charge rate to 8 amperes, one at 37 volts to decrease the charge rate to 4 amperes, and the last at 38 volts to turn the charger off. For a more detailed description of the battery chargers, see reference 4.

The trip points of the positive battery charger were measured over the temperature range tested and found to be independent of temperature. A plot of this data is shown in figure 7. The negative battery charger was also tested and the data were essentially identical to that of figure 7.

Electrical Control Package

At each test point all relays, circuits, and overrides were exercised. All functioned correctly.

Also, at each test point the speed control calibration curve was checked for temperature effect. The frequency of the M-G set was varied and the power to the parasitic load was recorded and compared to the 25°C ambient curve. The calibration curve at each test point was within measurement accuracy of the original 25°C curve. No effect on the speed control calibration was observed over the range of temperatures tested.

The voltage-regulator-exciter (VRE) calibration was also checked by measuring the current in a simulated shunt field while holding line-to-neutral voltage and frequency constant. This parameter was also unaffected by temperature over the test range.

Brayton Control System

To simulate cold startup conditions, the Brayton control system was turned off as the temperature test points were changed and not turned on until the entire system had reached the desired temperature. When this condition was reached, the system was energized. Engine control was available immediately, although all temperature readings were not stable and the heat source control interlock opened. This was expected because it takes time for the thermocouple calibration ovens in the signal conditioner to reach temperature; as the ovens warmed up, the temperature readouts indicated the correct temperatures. The warm-up time was a function of the ambient temperature. At the coldest test point, -50°C, warm-up time was approximately 30 minutes. Within 5 minutes after the system was turned on, the speed alarm set points were checked. Figure 8 compares the effect of temperature on the set points. The small change in set point from 25 to -50°C (2 percent) shown on this figure is not significant for the system operation.

CONCLUDING REMARKS

The Brayton cycle electrical subsystem was tested as a system over a temperature range of 25 to -50°C and no problems were found. The test consisted of a simulated cold startup and collecting performance data within one-half hour after startup. Small variations in the efficiency of some components were observed and some small changes in alarm set points occurred; however, no failures occurred and component performance gave no indication that there would be any effect on the safe operation of the Brayton power generating system.

The most significant results were:

1. The efficiency of the inverter-pump-motor assembly combination decreased from 16 percent to 13 percent as the temperature decreased.

2. The output voltage of the inverter and the dc supply were independent of temperature. Also, the speed control characteristics were independent of temperature.

3. The battery charger trip points were essentially independent of temperature.

4. The Brayton control-system speed-alarm set points showed a small (2 percent) increase as the temperature decreased.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 23, 1971.

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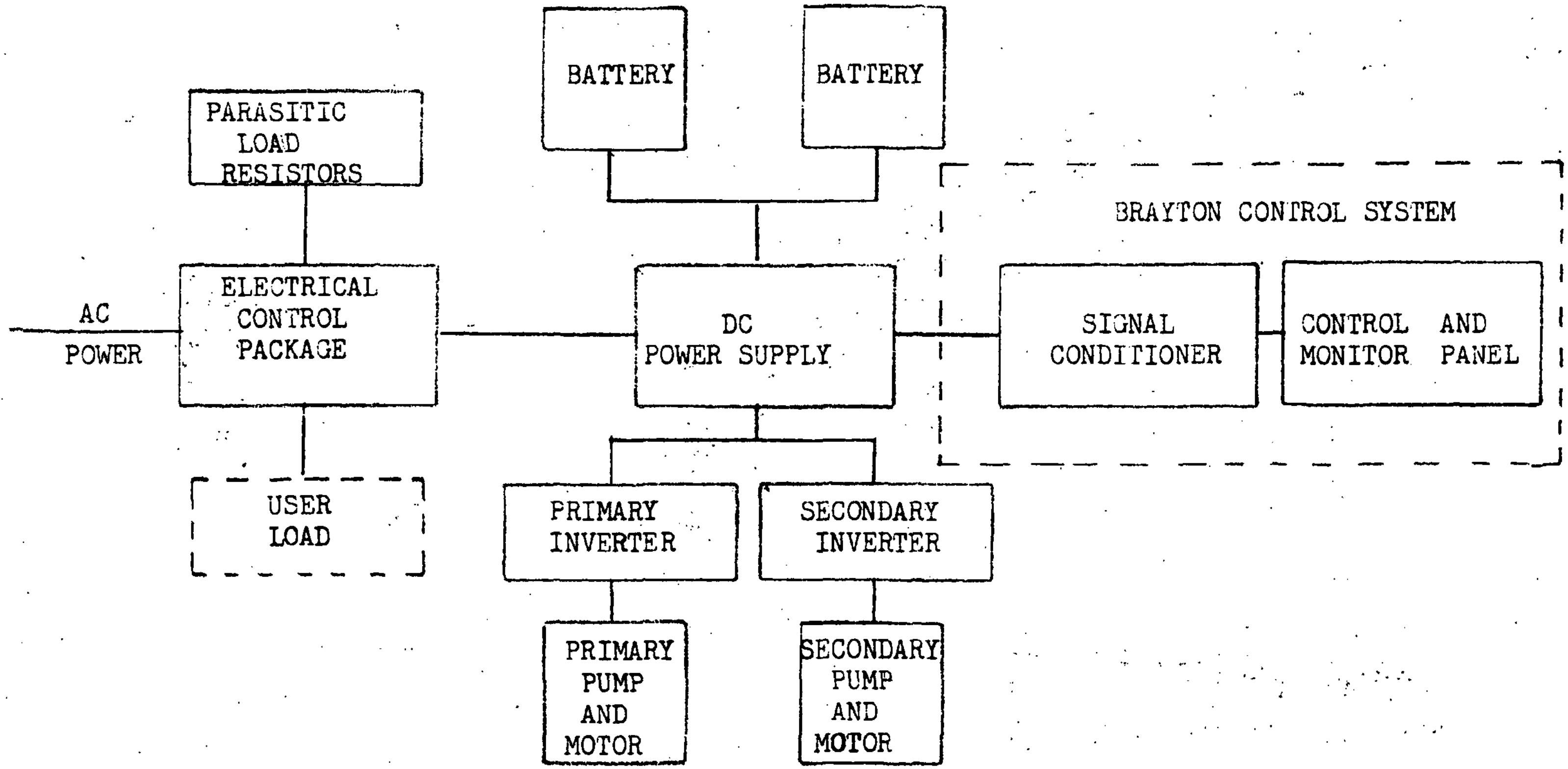

FIGURE 1. - SCHEMATIC OF BRAYTON CYCLE ELECTRICAL SUBSYSTEM

FIGURE 2 EFFECT OF TEMPERATURE ON PUMP INPUT POWER (INVERTER OUTPUT POWER)

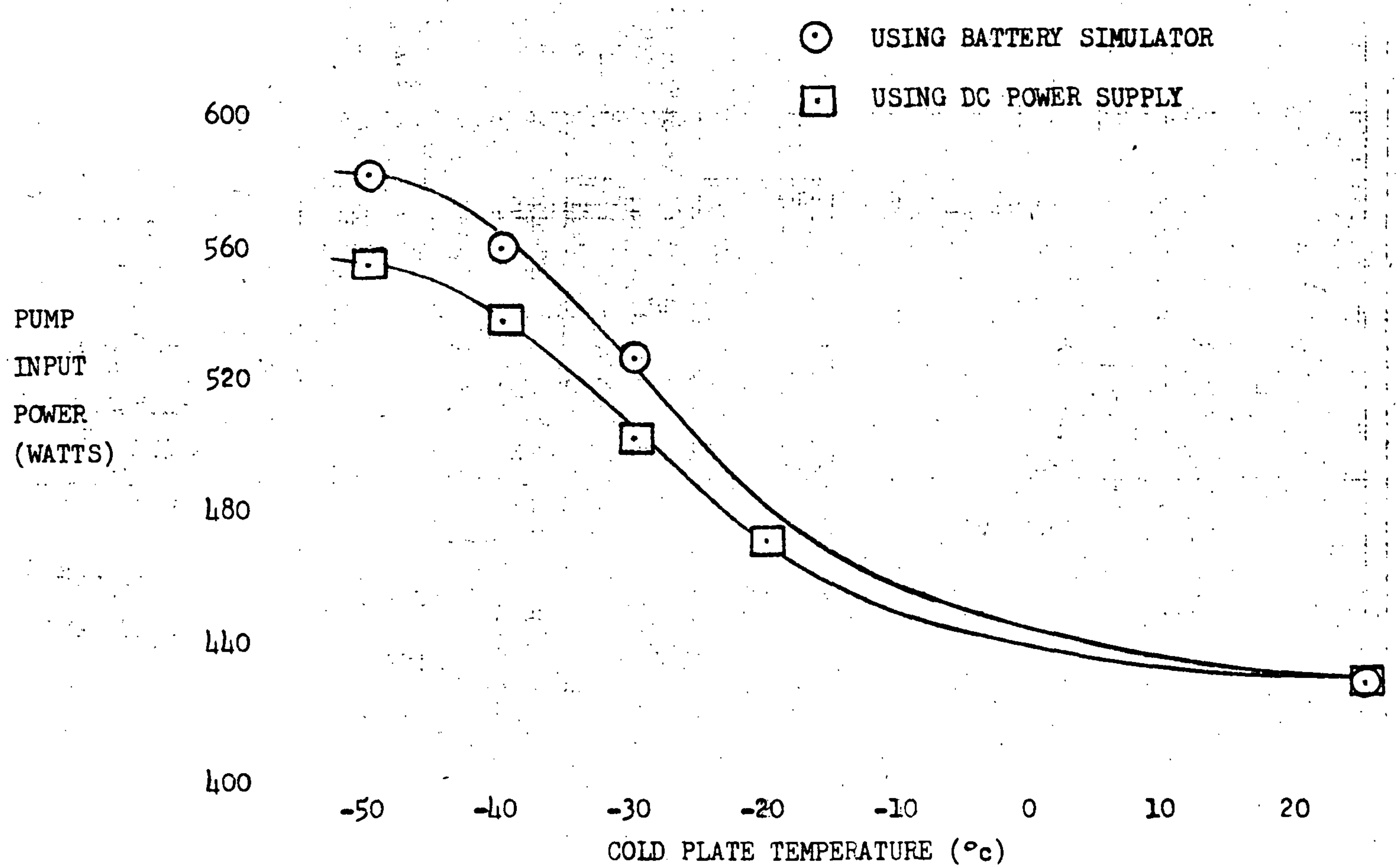

FIGURE 3 EFFECT OF TEMPERATURE ON PUMP FLOW RATE

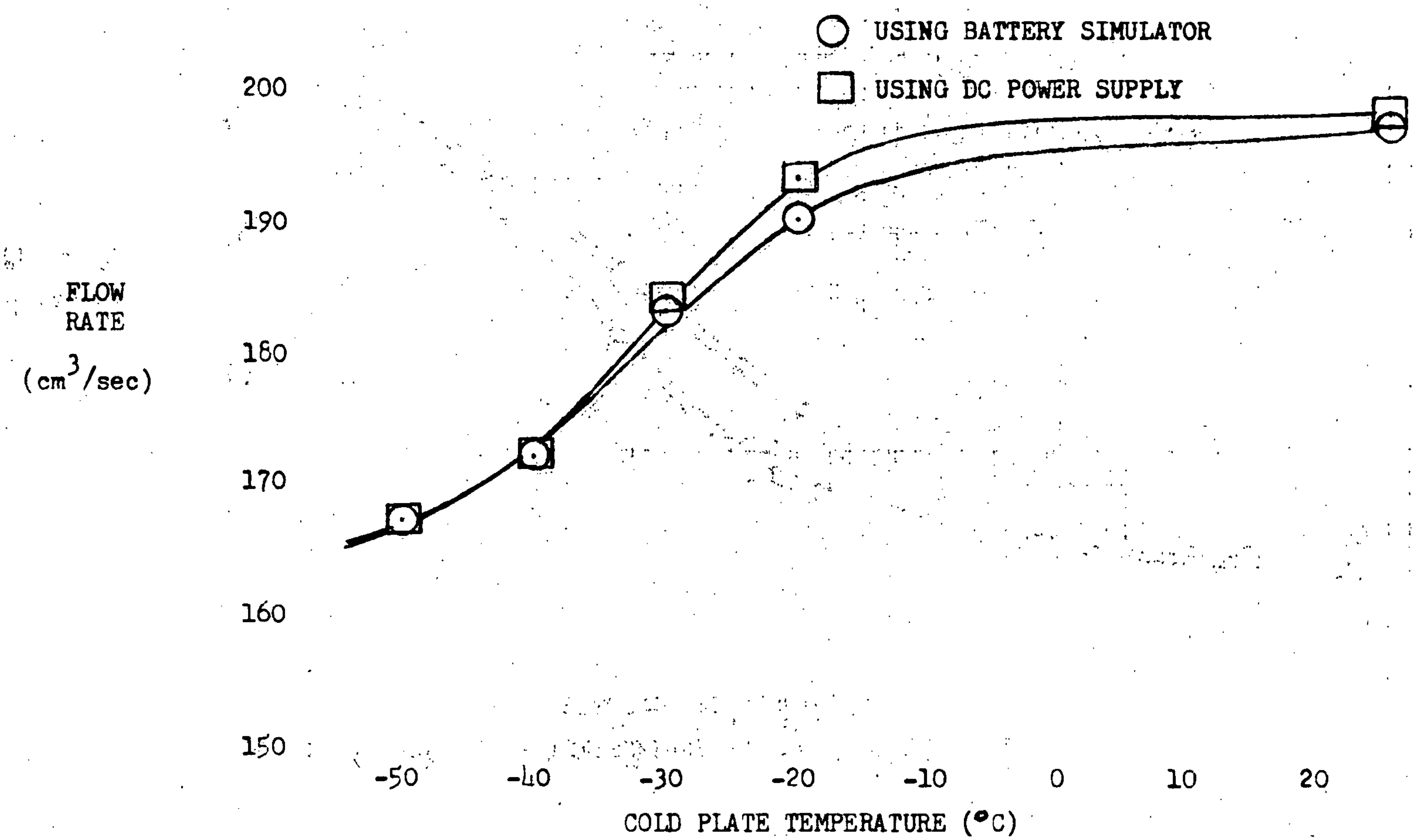

FIGURE 4 EFFECT OF TEMPERATURE ON PUMP MOTOR ASSEMBLY EFFICIENCY
ELECTRIC TO HYDRAULIC

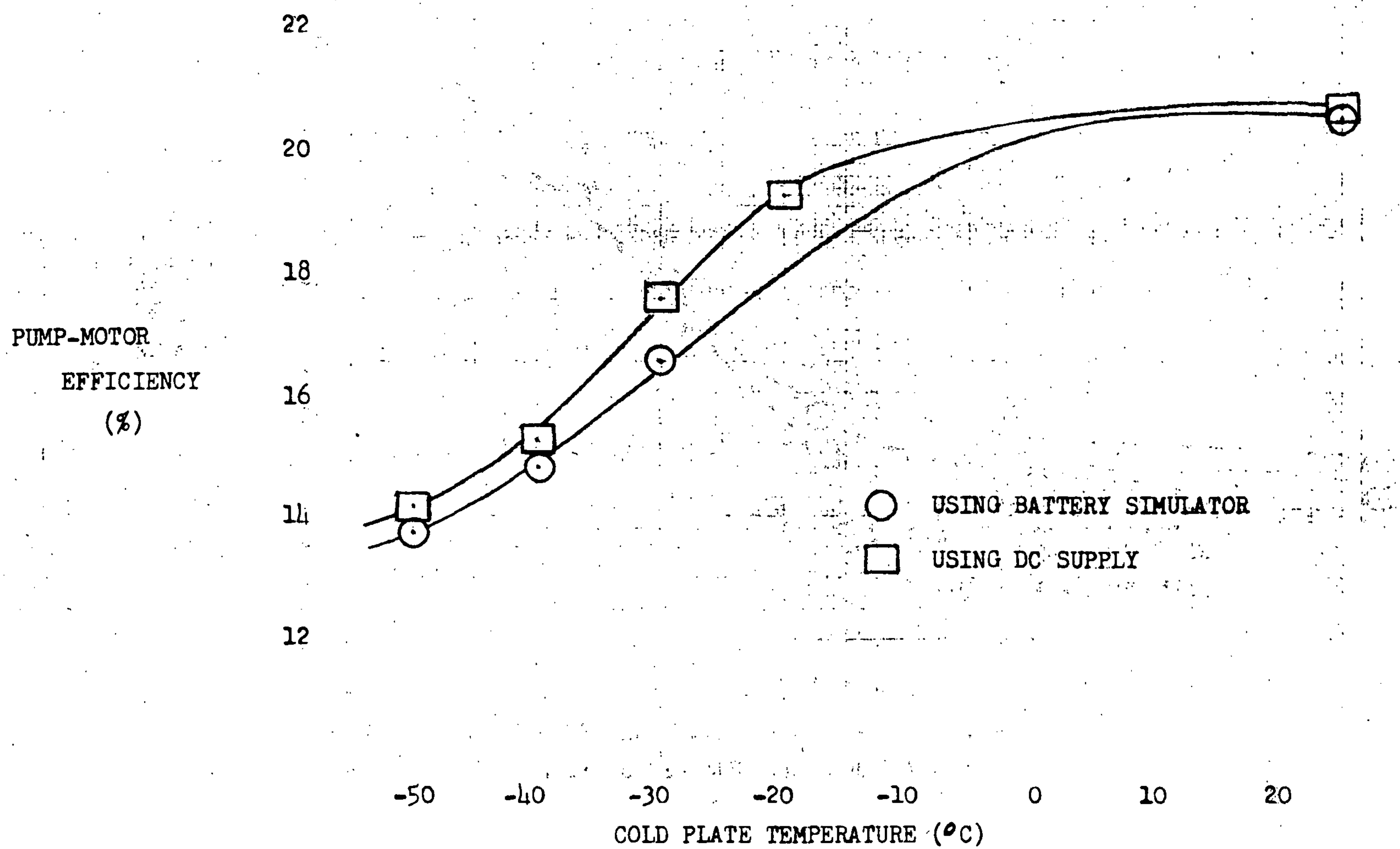

FIGURE 5 EFFECT OF TEMPERATURE ON INVERTER EFFICIENCY
POWER FROM BATTERY SIMULATOR

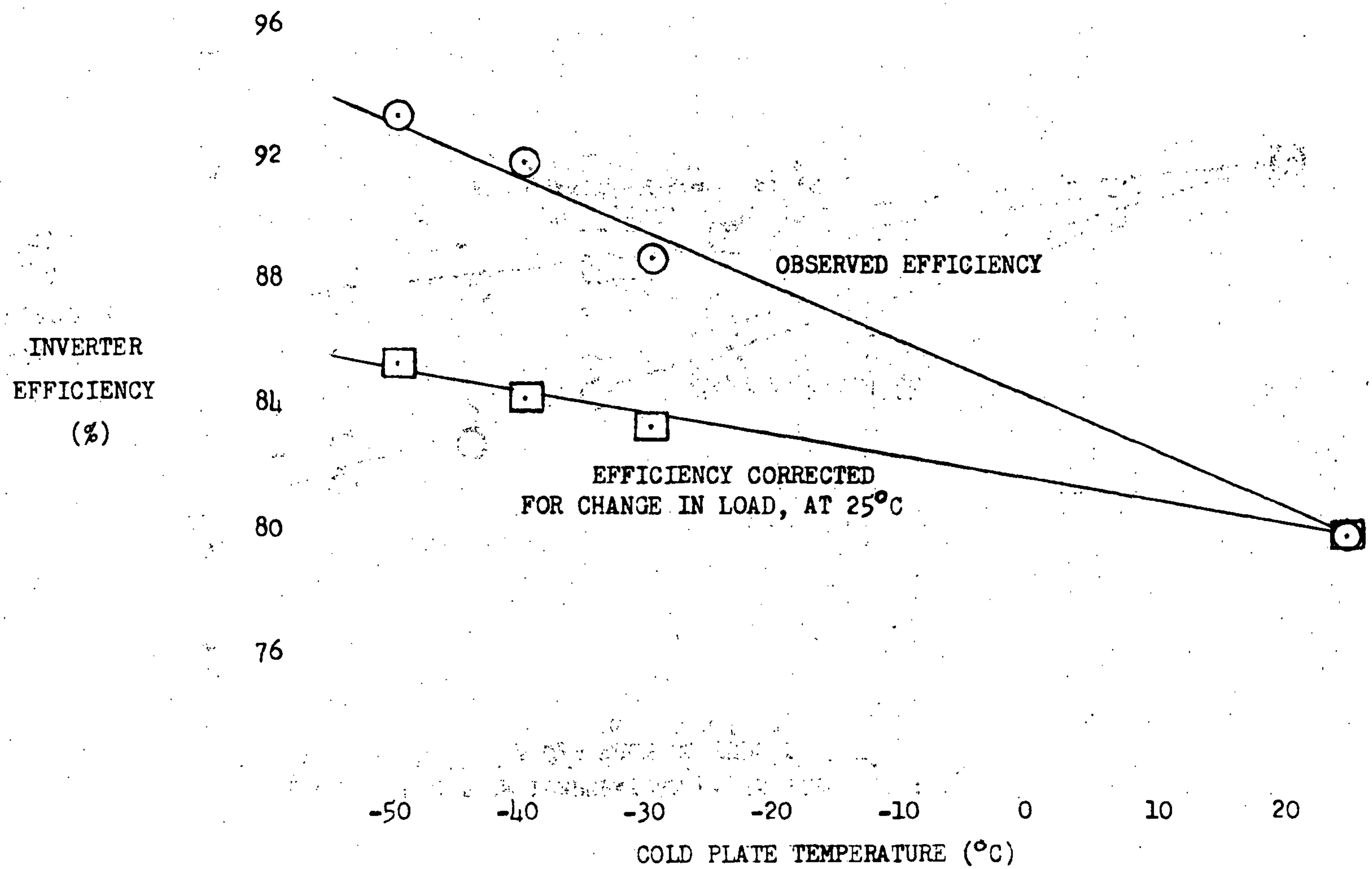

FIGURE 6 EFFECT OF TEMPERATURE ON INVERTER EFFICIENCY
POWER FROM DC SUPPLY

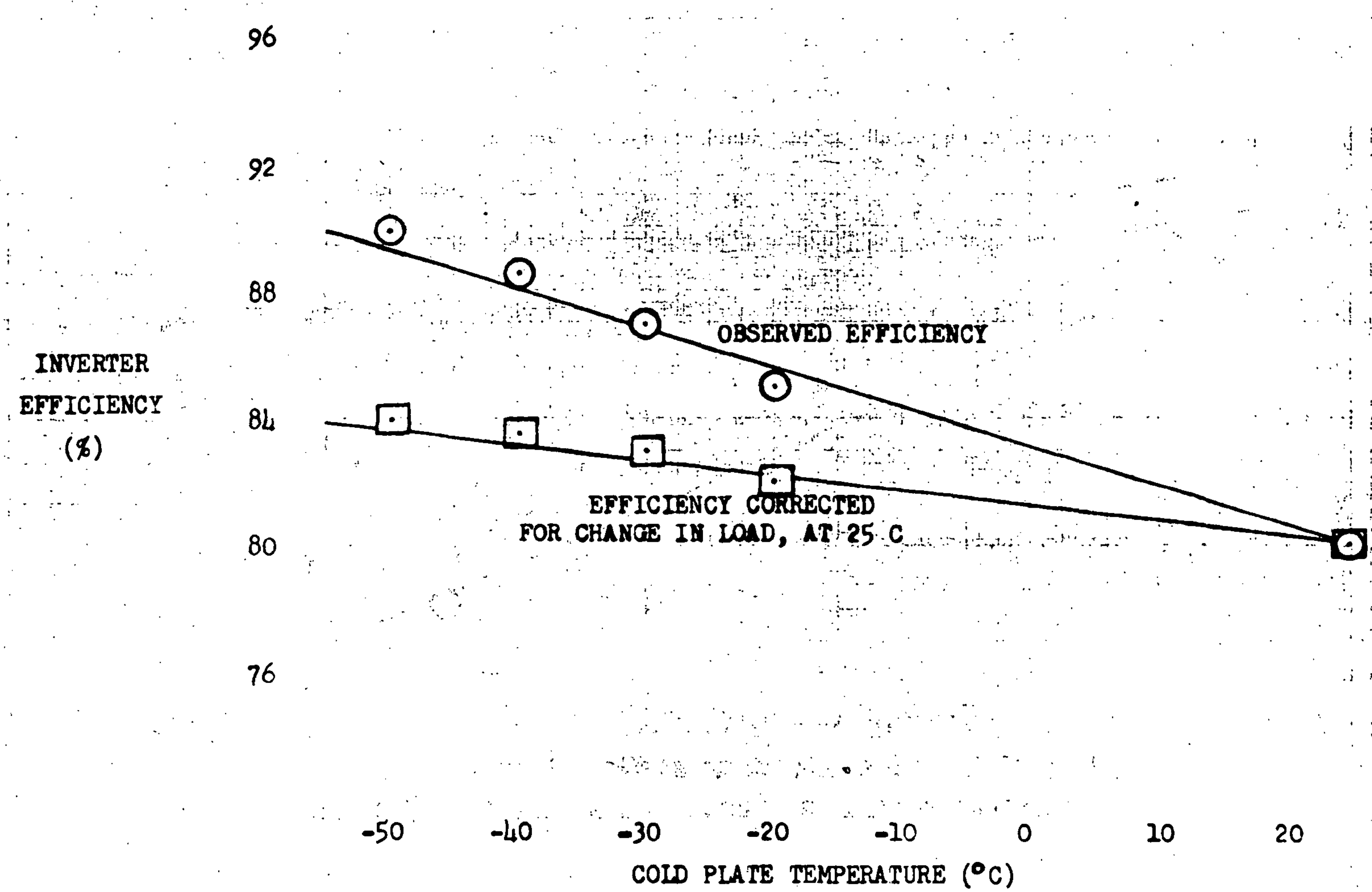

FIGURE 7 EFFECT OF TEMPERATURE ON BATTERY CHARGER TRIP POINTS

POSITIVE BATTERY

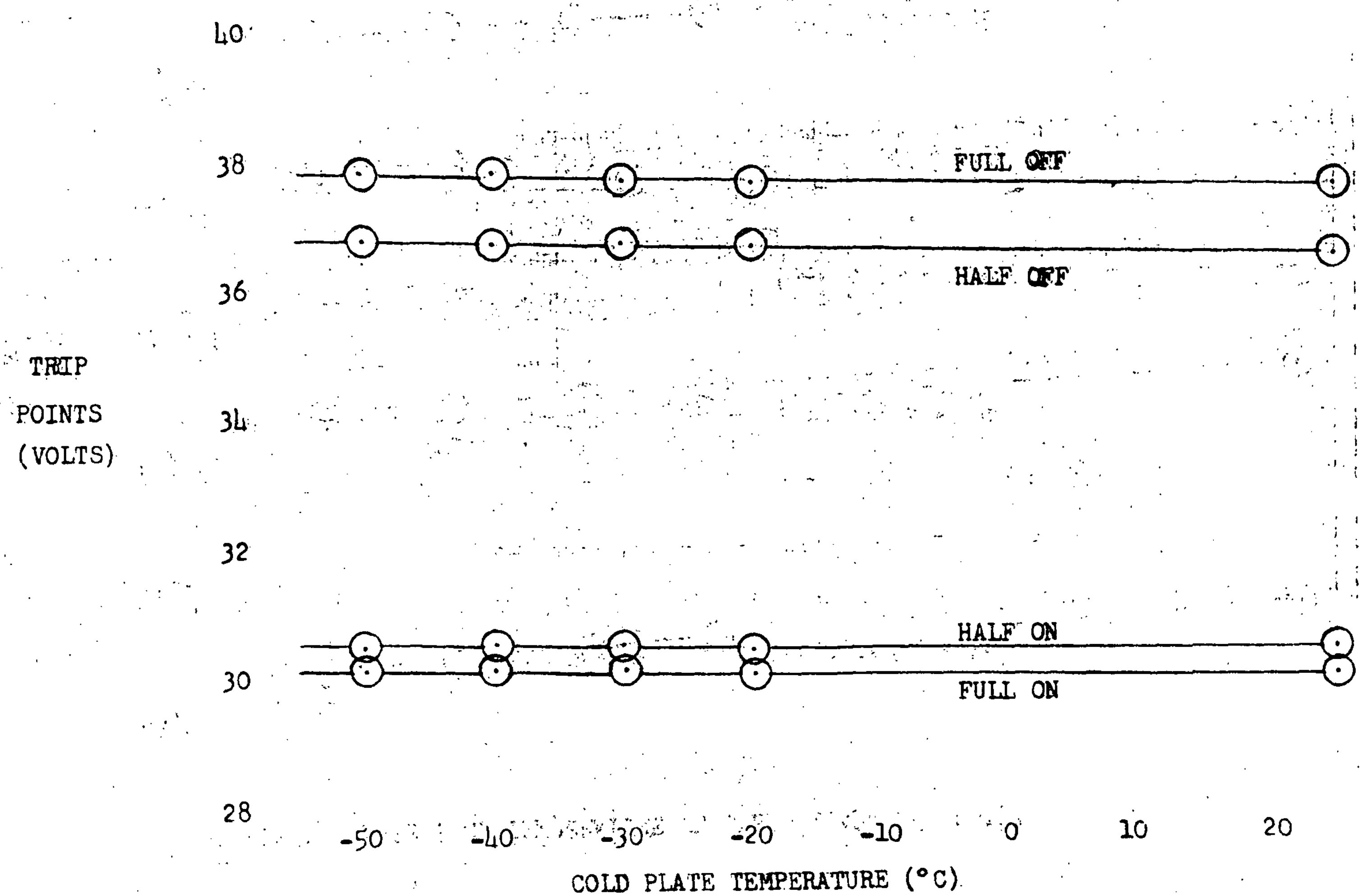

FIGURE 8 EFFECT OF TEMPERATURE ON SPEED ALARM SET POINTS